X Rays, Detonations, and Dead Zones

Livermore's high-flux radiography system can be used to image dynamic processes as they occur in metals, providing more detail on a material's strength and such mechanisms as spallation, fracture, and failure.

THE rapid, violent detonation of a high explosive (HE) generates supersonic shock waves that transfer energy by moving mass. According to Livermore physicist John Molitoris, trying to gather data on what happens to a material during this split second is often a case of "smoke and mirrors." He adds, "We hope the mirrors don't blow apart before the smoke ruins the view." But with the Laboratory's new high-flux radiography system (HFRS), the diagnostic capabilities for this harsh experimental environment have greatly improved.

The HFRS has no mirrors, and smoke is not a problem because the system can image right through it. Developed by a team of Livermore physicists, engineers, and technicians, the system combines 1-megaelectronvolt (MeV) and 450-kiloelectronvolt (keV) x rays to see clearly into the detonating material and examine the detonation as it twists, turns, and sometimes fails. The HFRS can provide a sequence of images showing a dynamic process as it occurs over time or a detailed three-dimensional (3D) reconstruction "snapshot" of images, all taken at the same time. The details revealed in these images are helping scientists better understand the physical processes in an HE detonation and in shocked materials.

Imaging the Tough Stuff

Molitoris first conceived of such a system about 5 years ago while conducting fragmentation experiments in Livermore's High Explosives Applications Facility (HEAF). "We were using HE detonations to investigate the dynamic failure of steel, watching cracks form and catching the resulting fragments," says Molitoris. "Catching the fragments is straightforward, but we needed radiography to observe the dynamics of crack formation and metal failure. The HEAF gun tank had a rudimentary x-ray capability, which we used for shadowgraphic imaging. By adding a 450-keV x-ray system in the tank, we started to develop a more powerful radiography system."

X-ray images taken with this new setup provided much more detail on the hydrodynamic processes. "We could distinguish shock waves formed from detonating HE and even the detonation front inside the steel pipe," says Molitoris. "When I saw these first images, I knew we had the beginnings of a powerful diagnostic tool."

A pilot system was developed in the HEAF gun tank to test different concepts for the final HFRS. With support from the Laboratory Directed Research and Development (LDRD) Program and later the Defense and Nuclear Technologies Directorate, Molitoris assembled the technical team for the HFRS project.

Bill Gilliam and Larry Crouch from DNT set up the facility operations. Installation in the HEAF firing tanks was facilitated by Ernie Urquidez and Pat McMaster, also of DNT. Engineering's Jan Batteux, Hank Andreski, Jim Travis, Brad Bratton, Gurcharn Dhillon, Gary Steinhour, and Rick Palmer designed and implemented both phases of the system. Chuck Cook from DNT was the radiographer, and scientist Raul Garza helped design and carry out the experimental program.

In the first test of the HFRS, Molitoris and his team received LDRD funding to explore the regime of warm, dense matter. Because this regime marks the transition between solids and plasmas, it is a particularly difficult region for recording experimental data. Thus, to evaluate the new system, the Livermore team used the HFRS to image shock waves in aerogels.

"We learned a lot about warm, dense matter and x-ray systems," says Molitoris, "and eventually outgrew the gun tank. This past year, we assembled the present HFRS in the HEAF spherical firing tank, which has more surrounding room and access ports. Now, we can combine dynamic x-ray imaging with diagnostics such as fast framing cameras, spectroscopy, velocimetry, and embedded fibers—all of which provide even more detail on the experiments."

The current HFRS uses two 1-MeV x-ray sources and two 450-keV sources to image detonations and shock waves in materials as diverse as aerogels and tantalum. The four sources were modified to produce higher currents and, thus, generate a higher flux of x rays. The HFRS is designed so that x-ray sources can be arranged in different experimental setups and triggered independently. For example, x-ray flashes can be staggered over time, as in a short movie, to provide a sequence of images that show a process as it evolves. Pulses also can be fired simultaneously, producing images that can be combined for 3D reconstruction of a dynamic process.

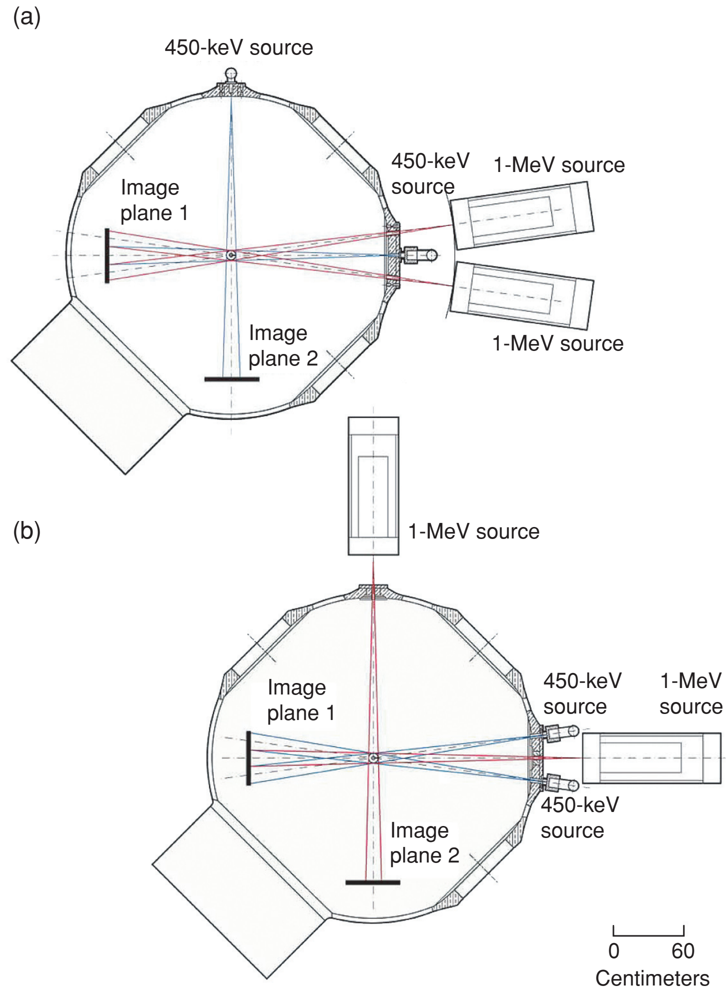
The team is considering other options for viewing the data in 3D. "We're working with physicist Maurice Aufderheide to explore a configuration that will act like a pair of eyes and produce stereoscopic images," says Molitoris. "Stereoscopic images can help us determine, for example, which side of a cylinder is fragmenting during detonation. Without the 3D aspect, we can't tell whether the near wall or the far wall is breaking up."

With the system's 25-nanosecond time resolution and 0.1-millimeter spatial resolution, scientists are imaging details never before seen in the detonation process. Recent experiments conducted with chemist Clark Souers focused on observing what happens when detonation propagates around a corner. "Understanding detonation propagation around corners and in even more complex geometries is vital for our stockpile stewardship work," says Molitoris.

In these experiments, a hemispherically shaped detonator is mated to a hemispherically shaped booster of the high explosive TATB. This piece is then placed in a well inside a cylinder of the high explosive LX-17, so that the cylindrical wall of LX-17 is above the TATB. When the TATB detonates, the detonation propagates hemispherically into the LX-17. Theory dictates—and code simulations indicate—that the detonation and its accompanying shock wave will "turn the corner" and continue up the wall of LX-17.

Reality, however, turned out to be quite different.

A time sequence taken with the HFRS shows that the detonation begins to fail as it hits the corner, and it continues to fail as it moves through the upper wall of LX-17. A region of nonreacting material, called a dead zone, forms as the shock front separates



The x-ray sources on Livermore's high-flux radiography system can be moved to different positions. Two experimental setups for the 450-kiloelectronvolt (keV) and 1-megaelectronvolt (MeV) sources are shown in (a) and (b). X-ray sources also can be set up to trigger independently, which provides a sequence of images over time, or simultaneously, so the images can be combined in a three-dimensional reconstruction of a dynamic process.

from the dying detonation. As the detonation front moves farther from the corner, it begins to propagate through the upper wall of LX-17, leaving behind the doughnut-shaped dead zone.

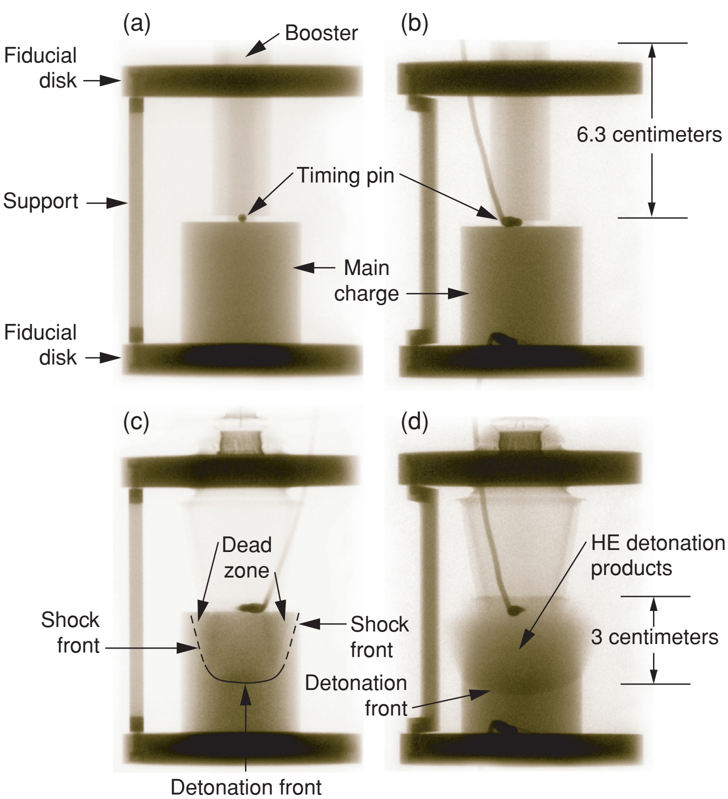
"The formation of a long-lasting dead zone was totally unexpected," says Molitoris. "Results such as these—which are not anticipated by theory—demonstrate why new diagnostics such as the HFRS and the resulting experimental data are important."

But what is it about turning a corner that causes a dead zone to form? "We don't exactly know," says Molitoris. "The discontinuity, the corner in this experiment, initiates the dead zone, but its formation is also affected by the type of HE used. More ideal energetic materials can turn corners quite well, but not TATB-based materials such as LX-17."

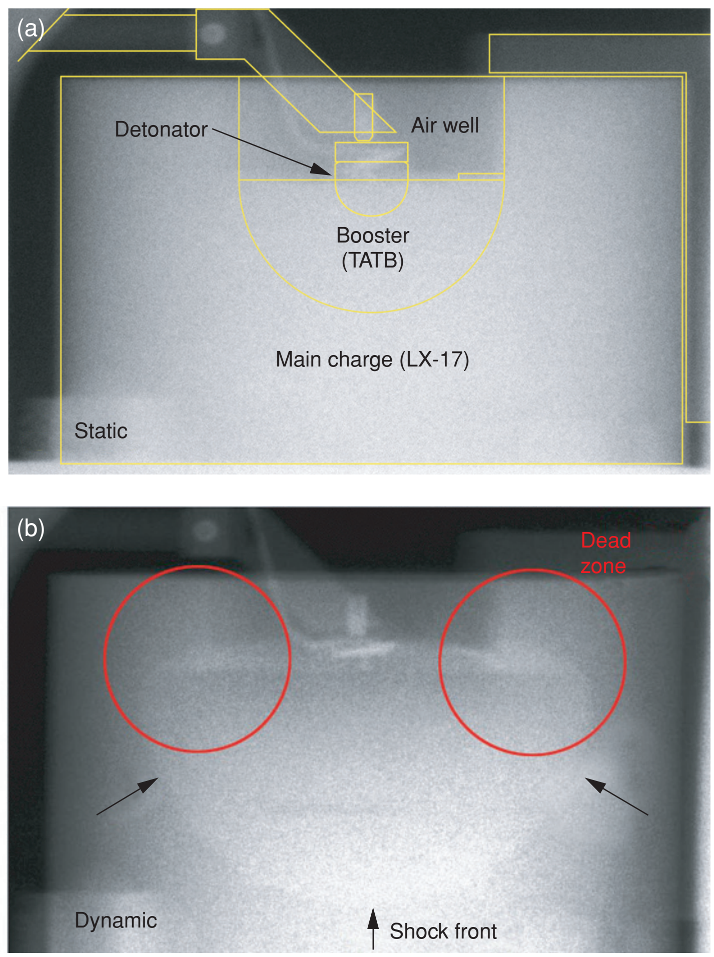
Experiments are helping the team study this phenomenon. "For instance, we're exploring whether temperature affects the size and structure of the dead zone," says Molitoris, "and we're examining other corner-turning geometries. All the information we gather will help us better understand the complex phenomenon of detonation. Modelers and theorists at Livermore need highly detailed data to improve the codes they're using in the Laboratory's stockpile stewardship work, so they can better predict detonation failure and quantify dead-zone formation."

The Future Is Shocking

The HFRS continues to churn out intriguing data from various experiments, revealing previously unseen details about the nature of detonation. In what may be the first radiographic study of shock



Radiographs show the setup for detonation experiments using two high explosives (HE): (a) LX-17 and (b) LX-04. (c) After the detonation begins, LX-17 has a weak detonation front and forms a dead zone. (d) In the LX-04 experiment, the detonation front progresses vigorously through the main charge.



A comparison of radiographs taken (a) before a high-explosive detonation and (b) 3.32 microseconds after the detonation starts to turn the corner shows regions of nonreacting material above the booster where detonation failed. These regions, or dead zones, persisted very late into the detonation process but were not predicted by theory or computer simulations.

behavior in aerogels, radiographic images of an LX-10 HE charge shocking silica aerogel clearly show the shock wave changing its shape as it propagates through the aerogel. "Once the shock wave hit the aerogel and was no longer supported by the detonation, the flat top of the shock front began to curve and broaden in the aerogel," says Molitoris. "With the earlier version of HFRS, we could almost see the Richtmyer–Meshkov mix structure in the transmitted shock. Our present system should be powerful enough to show those details."

The team is also exploring the difference in detonation and initiation in ideal and nonideal HE. In other experiments, the team is using the HFRS to measure the density variations that occur in metals shocked by a detonation, which will provide data on the viscosity of metals under dynamic loading. "It's been said that Lawrence Livermore is one of the few places that treats steel as a fluid," says Molitoris. "Up to now, our imaging capabilities did not provide enough detail inside the metal for us to quantify the density changes caused by shock loading. With HFRS, we can see those details, and we're now planning more difficult experiments with shocked metals."

The team also wants to investigate the process of deflagration in HE. Deflagration is a rapid chemical reaction that can quickly create heat, flame, sparks, or burning particles. Deflagrations generate separate subsonic pressure or shock waves instead of the mass flow of supersonic compression waves generated in HE detonations. As a result, the force of the expanding gas can be used to move an object—a bullet in a gun or a piston in an engine. In theory, deflagration is a slower process than detonation, and it can evolve into detonation. However, says Molitoris, "No one has ever been able to image that transition—up to now."

The HFRS is now operational and producing a wealth of information on material response to shock waves, detonation, and related hydrodynamic processes. The spherical firing tank at HEAF can handle up to 10 kilograms of (TNT-equivalent) HE, so it is ideal for relatively low-cost, focused experiments. The Department of Defense is interested in HFRS experiments to quantify mechanisms such as spallation, fracture, and failure. The team could also use the system to examine the detonation process in new advanced energetic materials that are being developed.

The Livermore team responsible for the high-flux radiography system is assembled between the 1-megaelectronvolt pulsers and the firing tank (from left): Hank Andreski, Sabrina Fletcher, Bradley Wong, Raul Garza, Jan Batteux, John Molitoris, Jim Travis, Pat McMaster, Larry Crouch, Brad Bratton, and Chuck Cook.

However, Molitoris says, "Our primary commitment is to support the Laboratory's stockpile stewardship mission by better understanding dynamic processes in metals and the corner-turning process in detonations. With the HFRS, we are helping Livermore and HEAF maintain the lead in detonation science."

—Ann Parker

Key Words: aerogel, deflagration, detonation, High Explosives Applications Facility (HEAF), high-flux radiography system (HFRS), hydrodynamics, x rays.

For further information contact John Molitoris (925) 423-3496 (molitoris1@llnl.gov).